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A SEARCH FOR A SUPERCONDUCTING EFFECT ON ALPHA PARTICLE DIFFERENTIAL ENERGY LOSS IN TYPE I SUPERCONDUCTORS

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A SEARCH FOR A SUPERCONDUCTING EFFECT ON ALPHA PARTICLE

DIFFERENTIAL ENERGY LOSS IN TYPE I SUPERCONDUCTORS

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The differential energy loss of non-relativistic charged particles is well approximated by the well known Bethe equation:

$$-\, dE/dx = \frac{4(ez)^2 e^2 ZN}{mV^2} \ln \frac{2mV^2}{I} \tag{1}$$

One might say that the gross effects of the energy loss process have been fairly well established by experiments. On the other hand, a unique possibility exists in the superconductors for looking into the finer aspects of the energy loss process. Within the confine of one material, the state of the electrons can change without other parameters changing, permitting the study of that effect alone on the interaction with the charged particles.

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The possibility that there may be a superconductivity effect in the energy loss process was proposed by Hayakawa and Kitao.[1] They predicted an excess energy loss of the order of one percent or less for a charged particle traversing a material in the superconducting state relative to that in the normal state. Following their argument, it is seen that all terms in the differential energy loss equation will be constant except the number N and the mass m of the electrons for a specific charged particle traversing a particular superconductor in the two states. That is:

$$(dE/dx)_n = kN/m \tag{2}$$

$$(dE/dx)_s = k(N - N_s)/m + kN_s/m_s \tag{3}$$

where k is a constant and subscripts n and s refer to the normal and superconducting state. Combining these two equations one obtains the fractional difference in the differential energy loss due to a superconducting effect:

$$\frac{(dE/dx)_s - (dE/dx)_n}{(dE/dx)_n} = \frac{N_s/m_s}{N/m} - \frac{N_s}{N} \tag{4}$$

The base for expecting the number to mass ratio of the superconducting state to be different from that of the normal state comes from measurements

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of the magnetic penetration depth, λ, and the London equation $\lambda = \left[(mc^2)/4\Pi e^2 N\right]^{1/2}$. In lead, for example, the measured value for λ is 4×10^{-6}cm leading to a value of $N_s/m_s = 2 \times 10^{49}$. The N/m for a material in its normal state can be approximated as $\left[(N_o \rho Z)/A\right]/m_o$, where N_o is the Avogadro's number, ρ is density, A is atomic mass, and m_o is the rest mass of the electron. The computed value for lead is 3×10^{51}. From this one would expect a difference of $2/3 \times 10^{-2}$ or of the order of one percent for the superconducting effect on the dE/dx in lead providing the term N_s/N is negligible. The authors of reference 1 believed N_s/N may be less than 10^{-4}. This latter point is reasonable also from the current theory, since only those conduction electrons within the phonon energy $\hbar\omega_o$ from the Fermi surface will form pairs of superconducting state. Dropping this term from equation (4) but taking into account the temperature dependence of N_s which is $1 - (T/T_c)^4$, we have;

$$\frac{(dE/dx)_s - (dE/dx)_n}{(dE/dx)_n} = \frac{N_s/m_s}{N/m}\left[1 - \left(\frac{T}{T_c}\right)^4\right] \tag{5}$$

The design of the experiment is shown in figure 1. The experimental chamber is an evacuated cylinder, the lower end of which is a detachable copper housing which holds an alpha particle source, the superconductor foil, and a carbon resistor. The copper housing provides three successive thermal shields between the detector and the superconductor foil. Direct thermal radiation from the charged particle detector to the foil via the collimation hole was reflected by a 1 mil aluminized mylar foil which covered the collimator hole. The temperature of the superconductor foil was monitored by a calibrated carbon resistor mounted on a plate used to hold the foil firmly in contact with the copper block. To insure thermal contact the foil was sandwiched between gold leaf where metal to metal contact was made. The charged particle source was a 10.6 hr ^{212}Pb source which in its decay to stable ^{208}Pb emitted alpha particles of 8.776 MeV, 6.047 MeV, and 6.086 MeV. The energy resolution of the detection system made it impossible to separate the pair of 6 MeV alphas. Consequently in further discussion only two alpha particle energy groups will be considered, 6.06 MeV and 8.78 MeV. The superconductor foil was positioned so that it covered only about one half the collimator hole. Consequently about one half of the alpha particles arrived at the detector "undegraded" in energy thereby serving as an internal energy calibration for the system. The whole assembly was placed in a liquid ^{4}He bath which could be pumped down to 1.7° K. Temperatures greater than 4.2° K were obtained by lowering the ^{4}He bath level until the required foil temperature could be maintained by the thermal heat leak down the chamber walls. To place the Tin (T_c = 3.69° K), Vanadium (T_c = 5.1° K) and Lead (T_c = 7.26° K) foils in the superconducting state the bath was pumped as hard as possible. A measurement was begun when the temperature of the foils reached 1.9° K and generally decreased to 1.7° K or 1.8° K over the period of a measurement, (normally 90 to 120 minutes). The normal state was obtained for Sn by using liquid ^{4}He at atmospheric pressure. Measurement on V and Pb in the normal state were begun when the foil temperature reached about 10° K. The temperature control was rather poor and usually the foil temperatures had risen to 20° K to 40° K during a measurement. This poor temperature control was not considered a problem for the following reason. Early in these measurements the dE/dx in Vanadium was measured a number of times at a bath temperature of 77° K and 4.2° K. Subsequent investigation showed that the actual foil temperature due to heat leaks was above the transition temperature of Vanadium which lead to the final design of the test chamber. However, it was determined that the dE/dx at both temperatures was the same within the statistical accuracy of the measurements. One ^{212}Pb source allowed enough time for a series of about 5 measurements. The state of the foil was changed after each measurement. The detector temperature generally decreased in temperature from about 157° K to about 143° K during a series of measurements. This decrease in detector temperature broadened the alpha particle energy peaks slightly due to the temperature dependence of the ionization potential in a Silicon detector (ref. 2).

The data of a typical measurement is shown in figure 2 with the tin sample in the superconducting state at 1.7° K. The peaks of the 8.78 MeV and 6.06 MeV alpha particle groups will be referred to as "undegraded", although they are degraded in energy by the 1 mil aluminized mylar reflector foil. Their actual energies were 7.48 MeV and 4.20 MeV. The peak due to the 8.78 MeV alpha particle group degraded by the superconducting foil (with additional degradation in the mylar foil) is referred to as the degraded 8.78 MeV peak. The degraded 6.06 MeV alpha particle group is further down in energy and has been cut off by the bias amplifier. The relative energy loss in the superconductor foil is expressed as:

$$\delta = \frac{ch_{8.78} - ch_{8.78d}}{ch_{8.78} - ch_{6.06}} \qquad (6)$$

where $ch_{8.78}$ and $ch_{6.06}$ are the peak channels for the undegraded 8.78 and 6.06 MeV alpha particle groups, respectively, and $ch_{8.78d}$ is the peak channel for the 8.78 MeV alpha particle group degraded by the superconductor foil. In this manner, the data are self-compensating for any electronic drift which might have occurred during a measurement.

The position of the maximum of each peak was determined by computer least squares fitting a sixth order polynomial to the experimental data of the upper half of each peak and then determining the point at which the differential of this polynomial equalled zero. Both χ^2 and t tests indicated that a sixth order polynomial provided a sufficiently good fit to the data. The goodness of fit is graphically illustrated with the tin degraded peak data in part (a) of figure 3. Part (b) of this figure shows the calculated differential curve of this polynomial. The peak position is represented by the point x_o and was calculated from $dy/dx = 0$ by the interval-halving method. To estimate the uncertainty in the peak position, an assumption was made that the fitted polynomial curve had the shape of the "true" curve but was positioned improperly by an amount $\pm\Delta x_o$. Based on the hypothesis that the true curve occurs at the position $x_o\pm\Delta x_o$, the value Δx_o for each peak was determined such that a χ^2 test employing the experimental data and the polynomial translated by Δx_o rejected this hypothesis at the 1% confidence level. That is to say the probability (confidence coefficient) that the true position of the peak lay between $x_o - \Delta x_o$ and $x_o + \Delta x_o$ is 99%. The uncertainties in δ's were computed in the normal manner.

The value of $(\delta_s - \delta_n)/\delta_n$ for each superconductor foil contains the weighted average of all runs taken in the normal and the superconducting state. There is a greater than 99% chance that the upper limit for the absolute value of $(\delta_s - \delta_n)/\delta_n$ is no larger than the calculated uncertainty. The results summarized in table I show the dE/dx in the two states are equal to within ±0.15% for tin, vanadium and lead, which is not inconsistent with a null effect.

The possibility of improving on this experimental limit seems likely. It was observed that the width of the degraded alpha particle energy distribution was much too wide based on straggling theory and is attributed to the surface roughness of the superconductor foils which were prepared by a rolling technique. It is estimated a similar experiment employing higher energy alpha particles, which would allow thicker and more uniform superconductor foils to be used, would reduce the error in the absolute value of individual δ's to the order of 0.02%. Because of the absence of any calculations of this effect employing BCS theory no future measurements have been planned.

References

1. S. Hayakaw and K. Kitao, "Energy Loss of a Charged Particle Traversing Superconductors," Prog. of Theoretical Phys., 16, No. 2, 131-138 (Aug. 1956).

2. R. H. Phel, F. S. Goulding, D. A. Landis, and M. Lenzlinger, "Accurate Determination of the Ionization Energy in Semiconductor Detectors," Proc. of a Conference conducted by Subcommittee on Instruments and Techniques, 19-36 (1969).

TABLE I

Superconductor	Thickness mg/cm²	State*	$\delta = \frac{Ch_{8.78} - Ch_{8.78d}}{Ch_{8.78} - Ch_{6.06}}$	$\frac{\bar{\delta}_s - \bar{\delta}_n}{\bar{\delta}_n}$	Hayakawa and Kitao†
		n	0.535468±0.000847		
		n	0.535381±0.000707		
Sn	5.6	s	0.535455±0.000897	-0.0010±0.0015	0.014
		n	0.535981±0.000849		
		s	0.534572±0.001046		
		n	0.529906±0.000839		
		s	0.530070±0.000944		
Sn	5.6	n	0.530289±0.000968	-0.0006±0.0019	0.014
		n	0.531442±0.001359		
		s	0.530148±0.001438		
		s	0.536153±0.000734		
		n	0.535737±0.000777		
V	4.4	s	0.536283±0.000816	-0.0006±0.0015	
		n	0.537365±0.000934		
		s	0.536048±0.001407		
		s	1.704971±0.008436		
		n	1.696649±0.005309		
Pb	19.8	s	1.694917±0.005739	0.0011±0.0036	0.017
		n	1.701270±0.007524		
		s	1.703893±0.008480		
		s	0.666794±0.000892		
Pb	11.2	n	0.667571±0.000994	0.0013±0.0014	0.017
		s	0.667719±0.000765	0.0013±0.0014	0.017
		n	0.665183±0.001103		

*n, normal; s, superconducting

†Reference 1

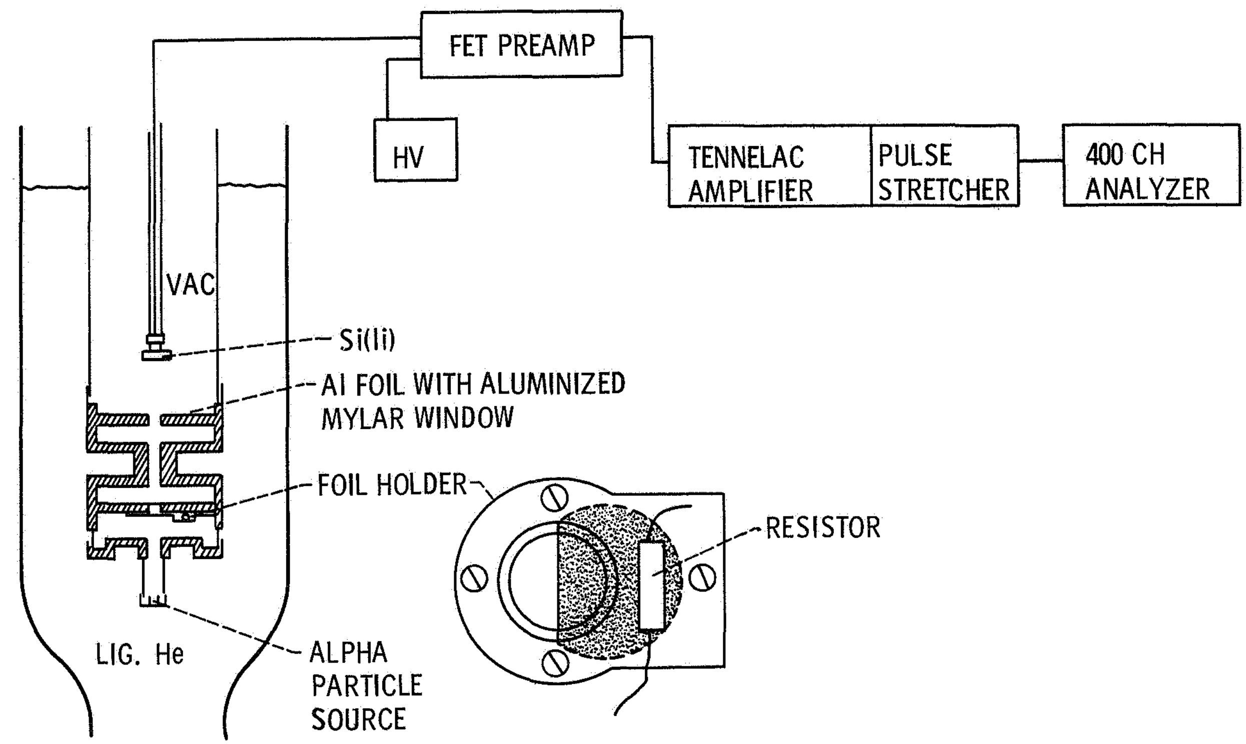


Figure 1. - Schematic diagram of the experimental chamber.

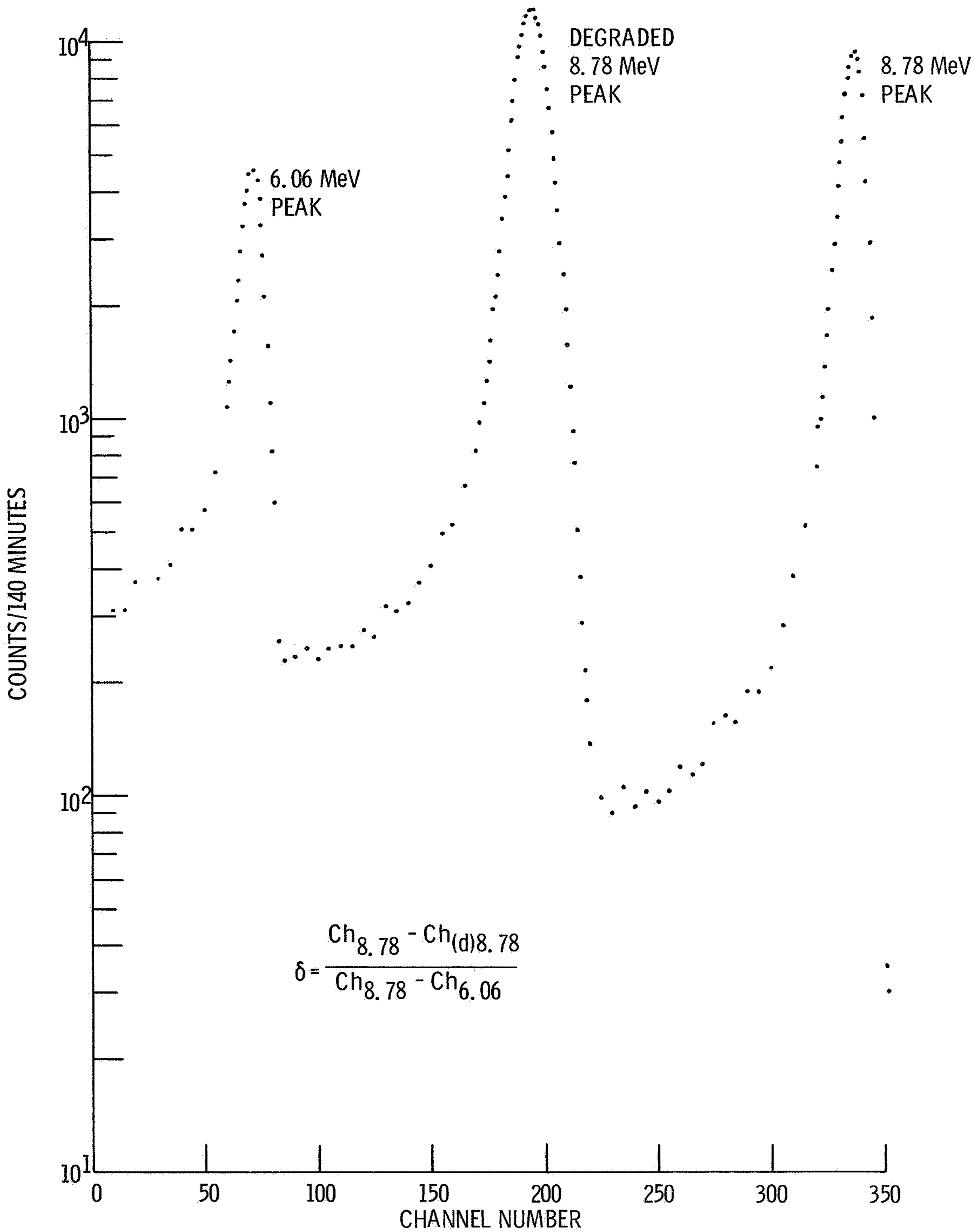
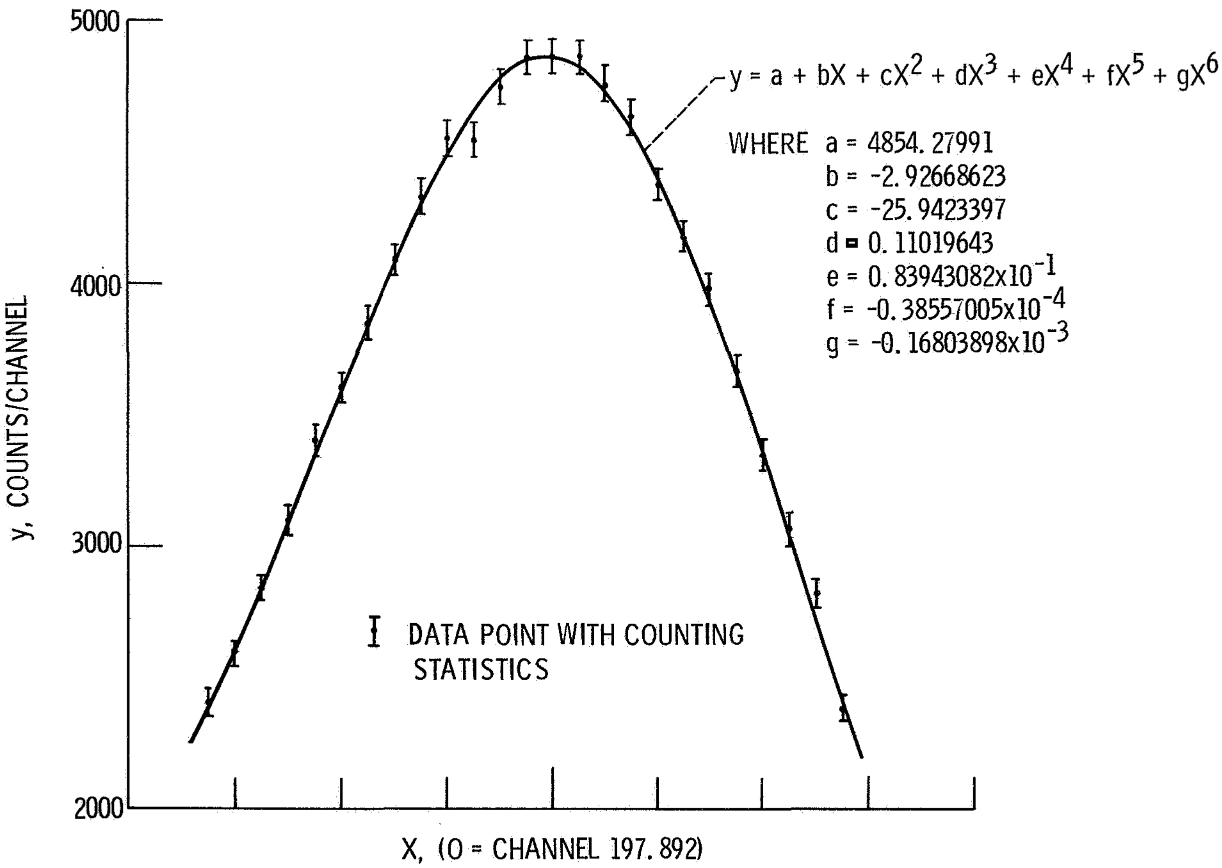
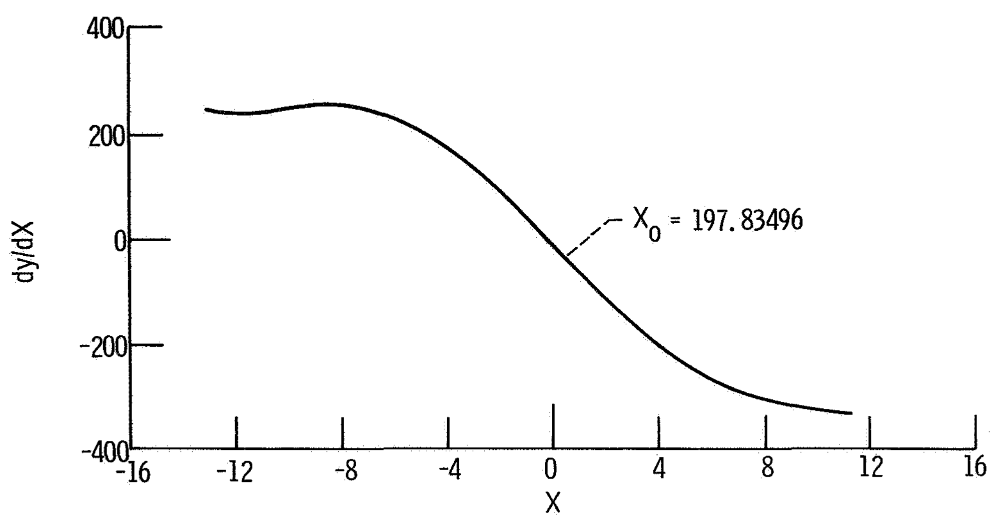


Figure 2. - Alpha particle pulse height distribution for a tin sample 5.6 mg/cm^2 in thickness at a temperature of 1.7° K. The actual energies of the α particle groups are: 6.06 MeV peak, 4.20 MeV; degraded 8.78 MeV peak, 5.75 MeV; and 8.78 MeV peak, 7.48 MeV.



(a) Calculated fit of a 6th order polynomial to the degraded 8.78 MeV peak shown in figure 2.



(b) Differential of the 6th order polynomial.

Figure 3